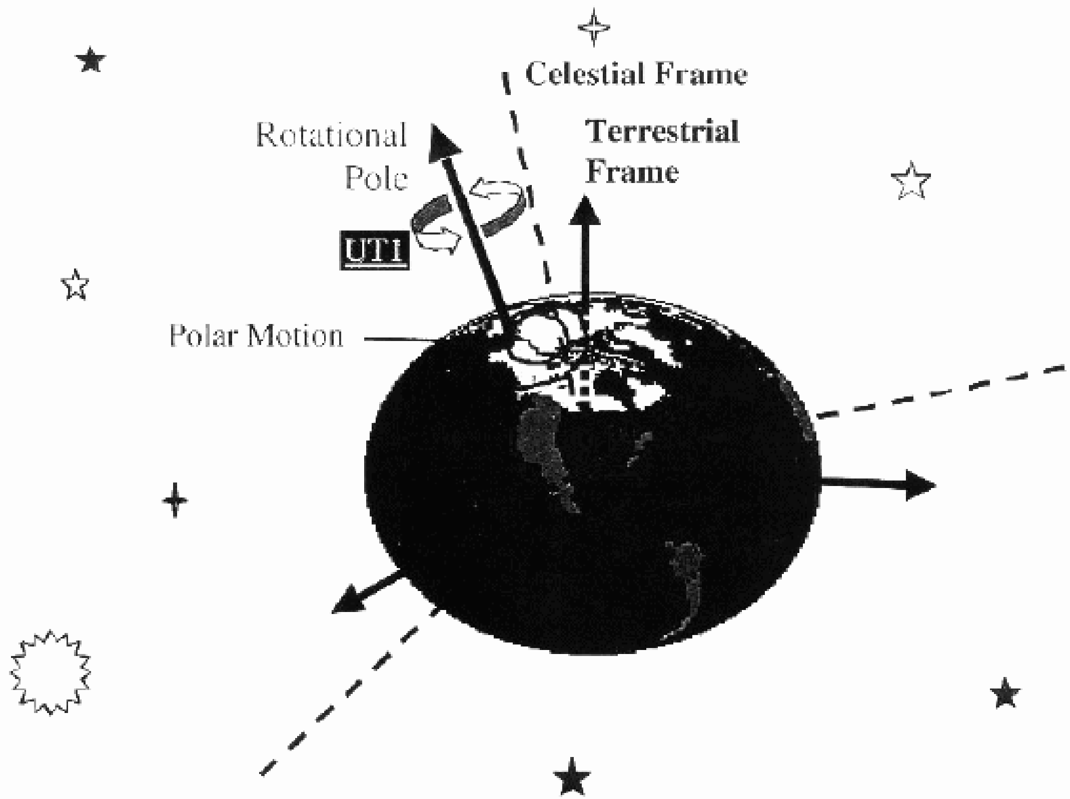
Monitoring of Earth Orientation Variables

Jim Ray
Earth Orientation Department
U.S. Naval Observatory

What are Earth Orientation Parameters?

- The time-varying angles which describe the rotation and wobble of the Earth as it spins in inertial space
- EPOs provide the link between:
  - ⋆ **terrestrial reference frame** — fixed to Earth
    non-inertial (rotating, etc.)
  - ⋆ **celestial reference frame** — fixed to quasars
    inertial (non-rotating)
  - ⋆ **TRF ← EOPs → CRF**
- Treated as 5 time–varying angles:
  - ⋆ **polar motion** — x,y coordinates of instantaneous pole location on Earth's surface (in TRF)
  - ⋆ **Universal time** — UT1 or, equivalently, excess length of day; angle about rotation (z) axis
  - ⋆ **nutation** — position of pole in celestial frame


Celestial Frame
Rotational Pole
Terrestrial Frame
UT1
Polar Motion

Why do EOPs Matter?

- Nearly all observations *of space objects* or *from space platforms* must be related to Earth points
  - ⋆ e.g., target locations
- Could use dense, global tracking networks to continuously locate satellites in TRF by geometric triangulation from the ground
  - ⋆ generally not practical (except for geostationary satellites)
- Instead, Newton's laws of motion give accurate description of satellite dynamics using sparse observations
- But physical laws only usable (simple) in inertial (non-rotating) frame
  - ⋆ otherwise, must introduce complex pseudo-forces

How are EOPs Used?

- Method to analyze Earth-based observations:
  - ⋆ apply transform: **TRF** $\rightarrow$ (EOPs) $\rightarrow$ **CRF**
  - ⋆ compute orbit in inertial frame using laws of motion
  - ⋆ transform back: **CRF** $\rightarrow$ (EOPs) $\rightarrow$ **TRF**
- Simple rotation matrix relation used:

$$\mathbf{CRF} = \mathbf{P} * \mathbf{N}(t) * \mathbf{R}(t) * \mathbf{W}(t) * \mathbf{TRF}$$

where

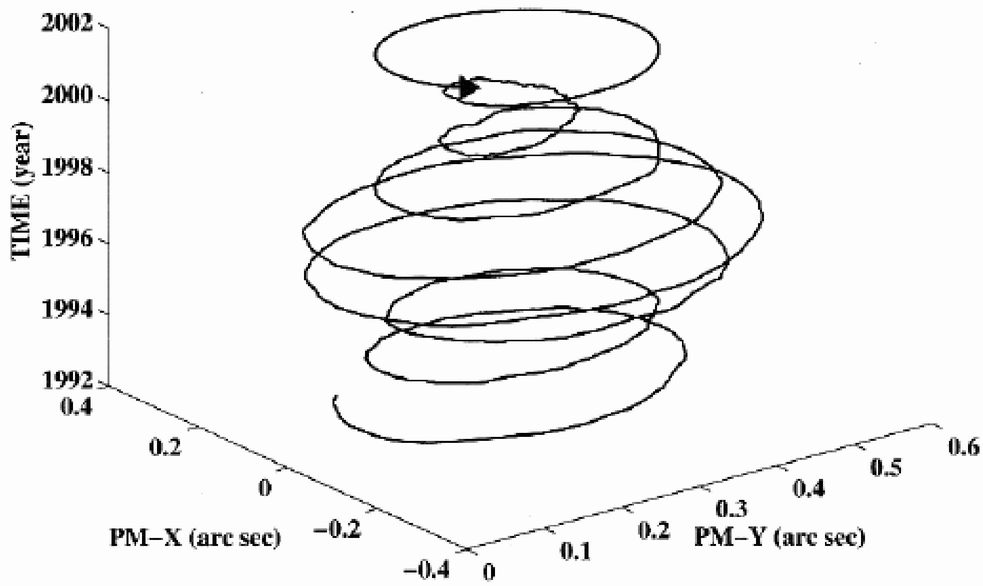
CRF = celestial (x,y,z) coordinates
TRF = terrestrial (x,y,z) coordinates
P = precession matrix
N(t) = nutation matrix
R(t) = rotation (UT1) matrix
W(t) = wobble (polar motion) matrix

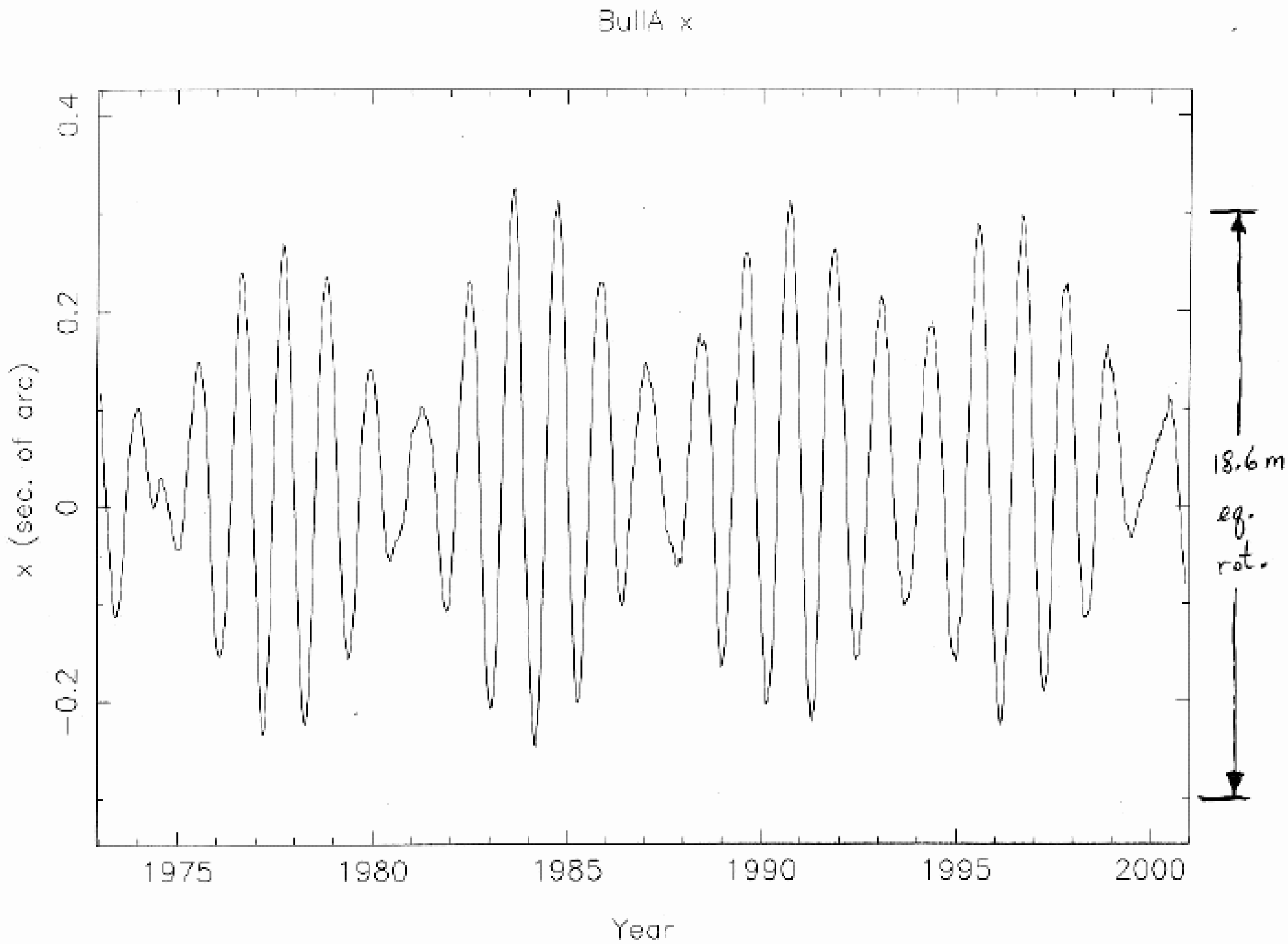
and the terms **N**(t), **R**(t), and **W**(t) are EOPs.

How Big are EOP Variations?

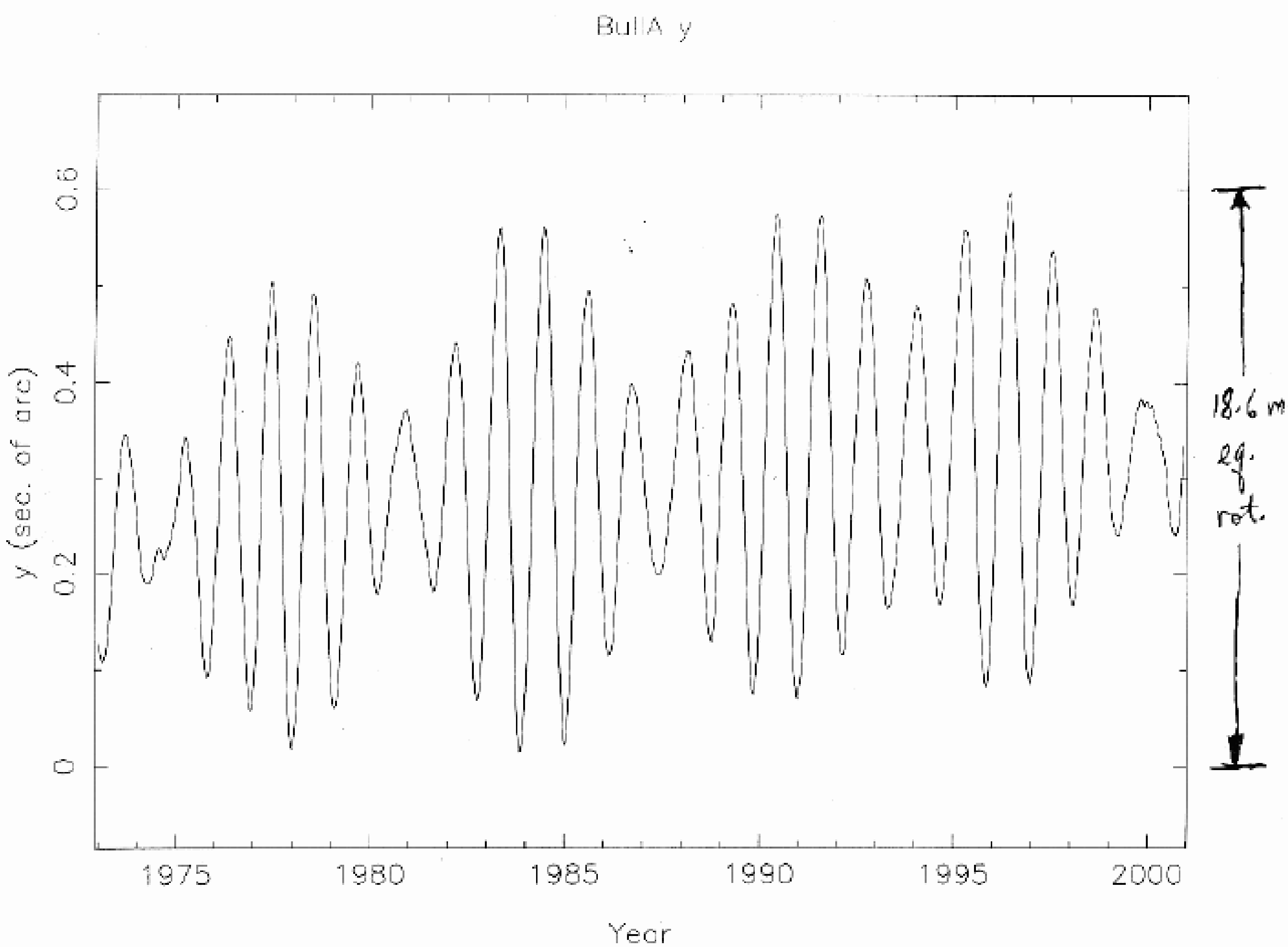
- variations on all time scales, from hours upward
  - ⋆ generally, larger changes over longer time scales
- **Polar motion** changes
  - ⋆ large annual periods (modulated)
  - ⋆ ± 600 mas range
    $\rightarrow$ nearly 20 meters of equatorial motion
- **Length of Day** changes
  - ⋆ large annual periods (plus known tides)
  - ⋆ ± 1 millisecond (ms) range for length of day over a year
    $\rightarrow$ nearly 0.5 meter of equatorial motion
- **UT1** changes
  - ⋆ integral of length of day changes
  - ⋆ small errors in length of day can accumulate to very large UT1 errors

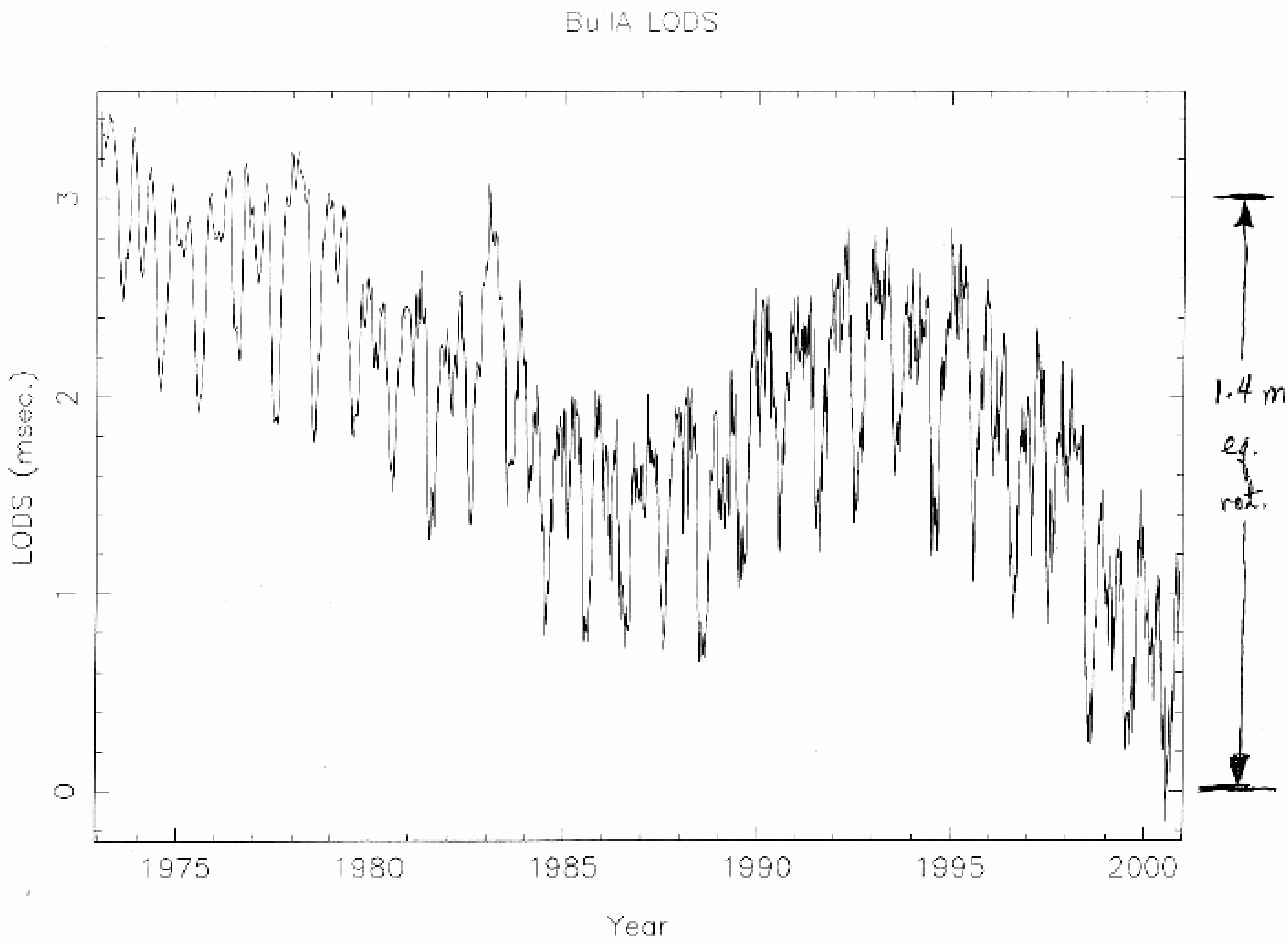
POLAR MOTION FROM 1992 TO 2002





BullA x
0.4
0.2
0
−0.2
x (sec. of arc)
1975
1980
1985
1990
1995
2000
Year
18.6 m
eq.
rot.


BullA y
y (sec. of arc)
0
0.2
0.4
0.6
1975
1980
1985
1990
1995
2000
Year
18.6 m
eq.
rot.

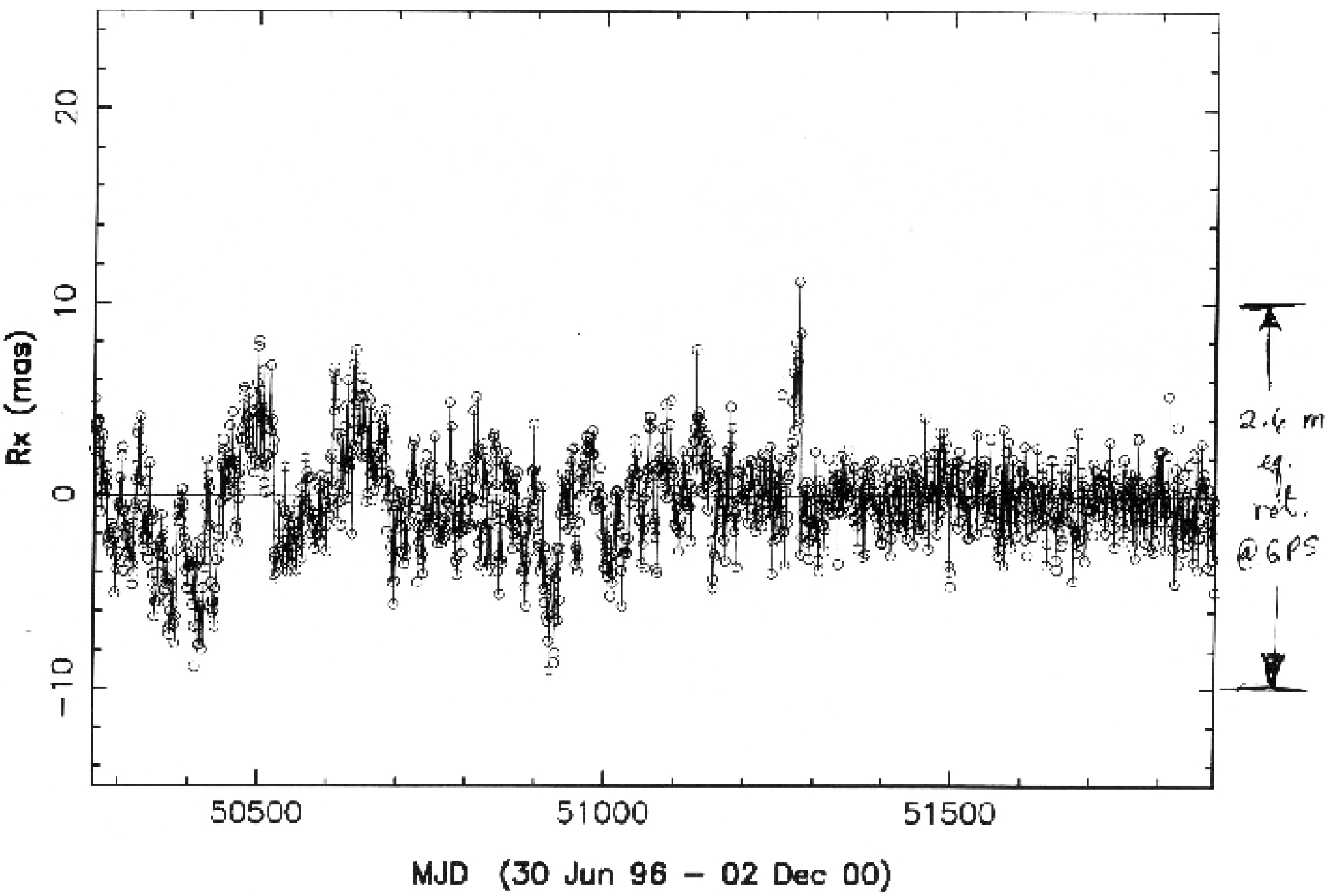


BulA LODS
LODS (msec.)
0
1
2
3
1975
1980
1985
1990
1995
2000
Year
1.4 m
eq.
rot.

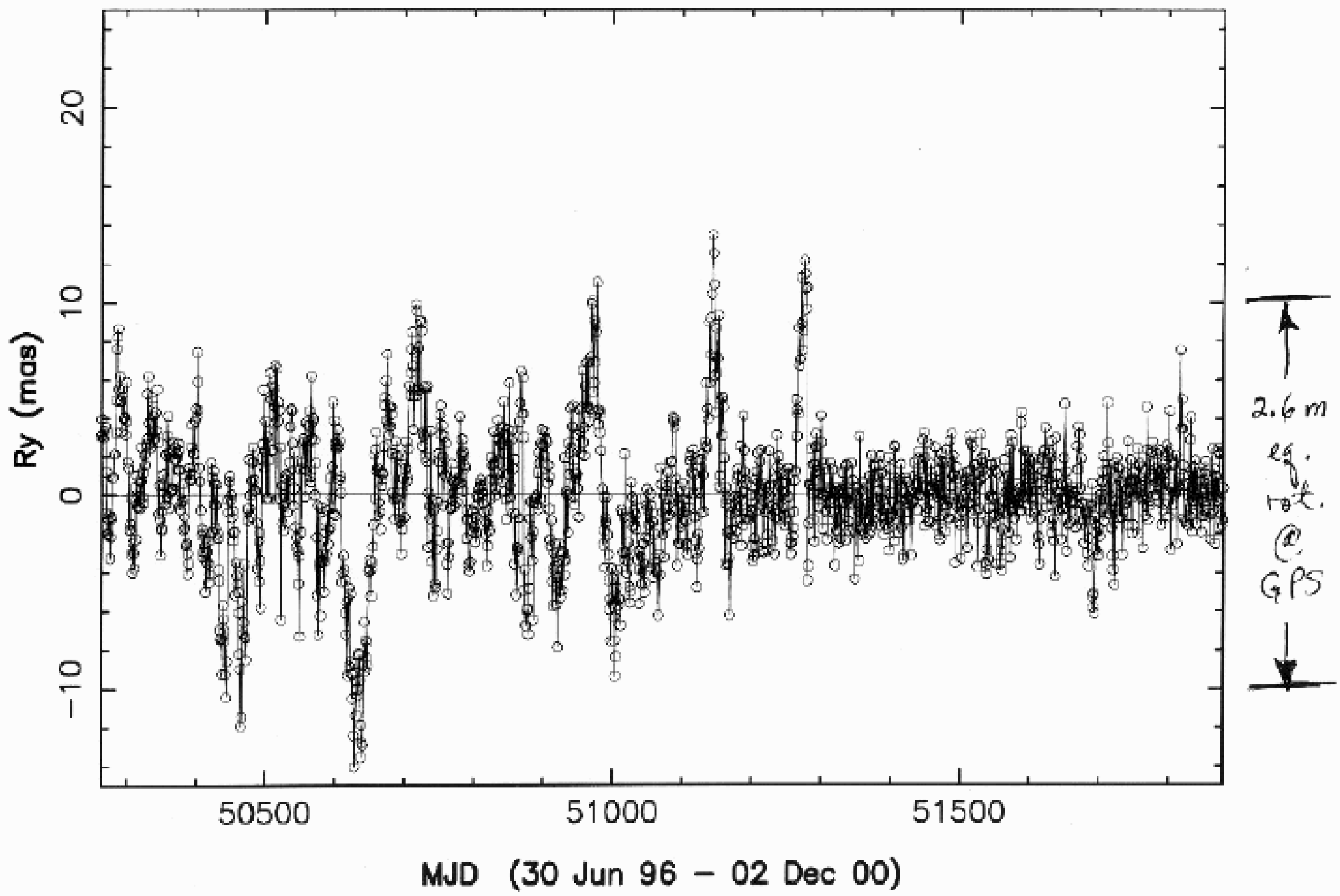
What is the Effect of EOP Errors?

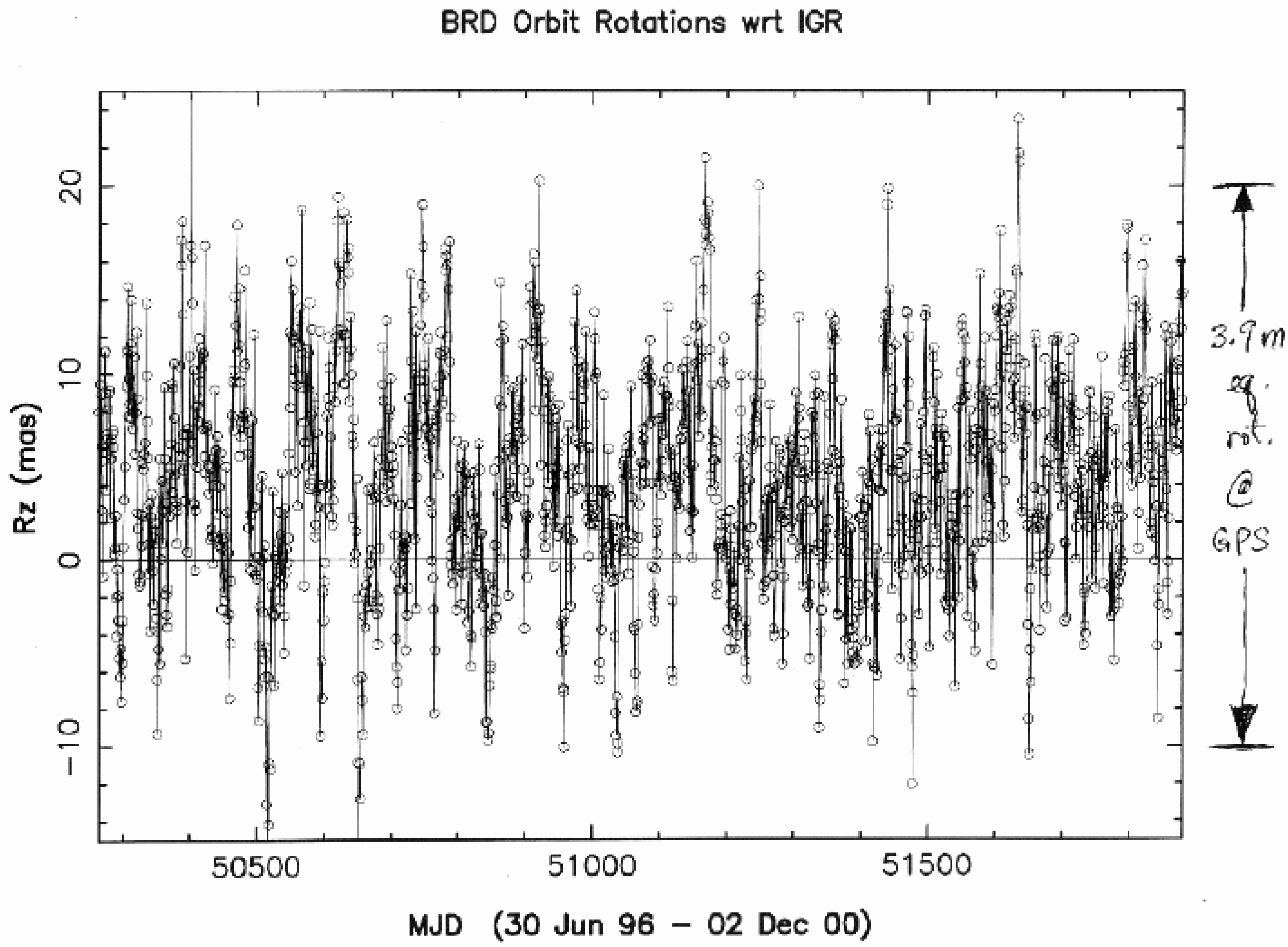
- Method to generate orbit predictions (for real-time use, e.g., broadcast GPS orbits):
  - ⋆ transform past tracking data (collected in TRF):
    TRF → (EOPs) → **CRF**
  - ⋆ **compute orbit** for observed period (in inertial frame)
  - ⋆ use laws of motion to **predict future orbit** (in inertial frame)
  - ⋆ transform back to TRF:
    CRF → (predicted EOPs) → **TRF**
- EOP prediction errors contribute directly to orbit rotation errors
- 1 milliarcsecond (mas) = 13 cm equatorial rotation @ GPS altitude
- GPS orbits show rotations up to ± 20 mas
  - ⋆ equivalent to **2.6 meters** equatorial variation

BRD Orbit Rotations wrt IGR



BRD Orbit Rotations wrt IGR





BRD Orbit Rotations wrt IGR
Rz (mas)
20
10
0
−10
50500
51000
51500
MJD (30 Jun 96 – 02 Dec 00)
3.9m
eq.
rot.
@
GPS

What Causes EOP Variations?

- **Nutation** — motion of celestial pole in CRF
  - ⋆ due to gravitational forces of Sun, Moon, and planets acting on non-spherical Earth
  - ⋆ accurately predicted by models
  - ⋆ prediction error <0.3 mas (<4cm @ GPS altitude)
- **Polar motion** — motion of pole in TRF
  - ⋆ due to exchange of angular momentum:
    Earth's crust ↔ atmosphere ↔ oceans
  - ⋆ crudely predictable
  - ⋆ prediction error ~0.4 mas/day (~5 cm/day @ GPS altitude)
- **UT1** — rotation rate
  - ⋆ due to exchange of angular momentum:
    Earth's crust ↔ atmosphere ↔ core
  - ⋆ very poorly predictable
  - ⋆ prediction error ~0.1 ms/day = ~1.5 mas/day (~20 cm/day @ GPS altitude)

How are EOP Variations Measured?

- Very long baseline interferometry (**VLBI**) — applied to multi-station radio astronomy of quasars
  - ⋆ measure all 5 EOP angles
  - ⋆ weekly EOPs (5 times per week UT1)
  - ⋆ very expensive
  - ⋆ multi-agency, multi-national effort
  - ⋆ International VLBI Service (IVS)
- Satellite laser ranging (**SLR**) — round-trip timing of laser pulses to satellites
  - ⋆ measures polar motion and length of day
  - ⋆ daily to few-day EOPs
  - ⋆ very expensive
  - ⋆ multi-agency, multi-national effort
  - ⋆ International Laser Ranging Service (ILRS)
- Global Positioning System (**GPS**) — radiometric timing using global tracking network
  - ⋆ measures polar motion and length of day
  - ⋆ daily EOPs; most accurate polar motion
  - ⋆ inexpensive network and analysis
  - ⋆ International GPS Service (IGS)

Where to Get Latest EOPs?

- International Earth Rotation Service (**IERS**)
  - ⋆ exists to provide EOP service to user community
  - ⋆ ensures consistent, high-accuracy results
  - ⋆ USNO serves as Rapid Service & Prediction Center
- *IERS Bulletin A* (Rapid Service & Predictions)
  - ⋆ prepared at USNO
  - ⋆ publication of recent past EOPs
  - ⋆ plus predictions up to 1 year in future
  - ⋆ based on multi-technique combination (VLBI, SLR, GPS)
- Access EOP products at
  - ⋆ *http://maia.usno.navy.mil/*
  - ⋆ web/ftp protocols
  - ⋆ also, e-mail subscriptions available